High-Precision Storage Ring for g-2 of the Muon and Possible Applications in Particle and Heavy Ion Physics *

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A new superferric magnetic storage ring with highly homogeneous field at 1.45 T and weak electrostatic focussing is described which has been set up at the Brookhaven National Laboratory (BNL), USA, for a precision measurement of the magnetic anomaly of the muon. The toroidal storage volume has a radius of 7 m and a diameter of 9 cm. Precision magnetic field determination based on pulsed NMR on protons in H_2O yields the field to better than 0.1 ppm everywhere within the storage region. Follow on experiments using the setup have been already suggested to search for a finite mass of the muon neutrino and to search for an electric dipole moment of the muon with significantly increased accuracy. The high homogeneity of the field suggests the usage of such devices as a mass spectrometer for heavier particles as well.

1. Introduction

Trapping of elementary particles in combined magnetic and electric fields has been very successfully applied for obtaining properties of the respective species and for determining most accurate values of fundamental constants. The magnetic anomaly of fermions $a = \frac{1}{2} \cdot (g-2)$ describes the deviation of their magnetic g-factor from the value 2 predicted in the Dirac theory. It could be determined for electrons and positrons in Penning traps by Dehmelt and his coworkers to 10 ppb [1]. Accurate calculations involving almost exclusively the "pure" Quantum Electrodynamics (QED) of electron, positron and photon fields allow the

* This article describes in part results from work performed by the muon g-2 collaboration at BNL and working groups on the muon neutrino mass and the muon electric dipole moment.

most precise determination of the fine structure constant α [2] by comparing experiment and theory in which α appears as an expansion coefficient. The high accuracy to which calculations in the framework of QED can be performed is demonstrated by the satisfactory agreement between this value of α and the ones obtained in measurements based on the quantum Hall effect [3] as well as the ac-Josephson effect and the gyromagnetic ratio of protons in water [4], or the number extracted from the very precisely known Rydberg constant [5] using an accurate determination of the neutron de Broglie wavelength [6] and well known relevant mass ratios [7]. Moreover, the excellent agreement of α values determined from the electron magnetic anomaly and from the hyperfine splitting in the muonium atom [8] may be interpreted as the most precise reassurance of the internal consistency of QED, as the first case involves QED of free particles whereas in the second case distinctively different bound state QED approaches need to be applied [9].

The anomalous magnetic moment of the muon a_μ has a $(m_\mu/m_e)^2 \approx 4 \cdot 10^4$ times higher sensitivity to heavier particles and other than electromagnetic interactions. They can be investigated carefully, as very high confidence in the validity of calculations of the dominating QED contribution arises from the success of QED describing this quantity for the electron.

For the muon a_μ has been measured in a series of three experiments at CERN [10] all using magnetic muon storage. Contributions arising from strong interaction amount to 60 ppm and could be identified in the last of these measurements.

At the Brookhaven National Laboratory a new dedicated experiment is being set up to determine the muon's magnetic anomaly which aims for 0.35 ppm relative accuracy meaning a 20 fold improvement over previous results. At this level it will be particularly sensitive to contributions arising from weak interaction through loop diagrams involving W and Z bosons (1.3 ppm). The experiment promises further a clean test of renormalization in weak interaction. The muon magnetic anomaly may also contain contributions from new physics [12,13,14]. A variety of speculative theories can be tested which try to extend the present Standard Model in order to explain some of its not yet understood features. This includes muon substructure, new gauge bosons, supersymmetry, an anomalous magnetic moment of the W boson and leptoquarks. Here this measurement is

Table 1
Sensitivity to new physics of the g-2 experiment at BNL aiming for 0.35 ppm relative accuracy.

new physics		sensitivity		other experiments
Muon substructure	Λ	$\geq$	5 TeV	LHC similar
excited muon	m_{μ^*}	$\geq$	400 GeV	LEP II similar
$W^{\pm}$-boson substructure	Λ	$\geq$	400 GeV	LEP II ~100-200 GeV
$W^{\pm}$ anomalous	a_W	$\geq$	0.02	LEP II ~0.05,
magnetic moment				LHC ~0.2
Supersymmetry	$m_{\widetilde{W}}$	$\leq$	130 GeV	Fermilab p$\overline{\text{p}}$ similar
right handed $W_R^{\pm}$-bosons	$m_{W'}$	$\leq$	250 GeV	Fermilab p$\overline{\text{p}}$ similar
heavy Higgs boson	m_H	$\leq$	500 GeV	
Muon electric dipole moment	D_μ	$\leq$	$4 \cdot 10^{-20} ecm$	

[a] for substructure $\Delta a_\mu \sim m_\mu^2/\Lambda^2$

complementary to searches carried out in the framework of other high energy experiments. In some cases the sensitivity is even higher (Table 1).

2. The Brookhaven g-2 Magnet

In the BNL experiment polarized muons are stored in a magnetic storage ring of highly homogeneous field B and with weak electrostatic focussing using quadrupole electrodes around the storage volume. The difference frequency of the spin precession and the cyclotron frequencies, $\omega_a = a_\mu \frac{e}{m_\mu c} B$, is measured, with m_μ the muon mass and c the speed of light, by observing electrons/positrons from the weak decay $\mu^\pm \rightarrow e^\pm + 2\nu$. For relativistic muons the influence of a static electric field vanishes [15], if $a_\mu = 1/(\gamma_\mu^2 - 1)$ which corresponds to $\gamma_\mu = 29.3$ and a muon momentum of 3.094 GeV/c, where $\gamma_\mu = 1/\sqrt{1-(v_\mu/c)^2}$ and v_μ is the muon velocity. The momentum needs to be met at the 10^{-4} level for a corresponding correction to be below the desired accuracy for a_μ. For a homogeneous field the magnet must have iron flux return and shielding. To meet this, the particular momentum requirement and to avoid magnetic saturation of the iron a device of 7 m radius was built. It has a C-shaped iron yoke cross section with the open side facing towards the center of the ring. It provides 1.4513 T field in a 18 cm gap. The magnet is energized by 4 superconducting coils carrying 5177 A current. The storage volume inside of a Al vacuum tank has 9 cm diameter.

The magnetic field is measured by a newly developed narrow band magne-

tometer system which is based on pulsed nuclear magnetic resonance (NMR) of protons in water. It has the capability to measure the field absolute to ≈50 ppb [16]. The field and its homogeneity are continuously monitored by 366 NMR probes which are embedded in the Al vacuum tank and distributed around the ring. Inside the storage volume a trolley carrying 17 NMR probes arranged to measure the dipole field and several important multipole components as well a fully computerized magnetometer built from all nonferromagnetic components is used to map the field at regular intervals. The accuracy is derived from and related to a precision measurement of the proton gyromagnetic ratio in a spherical water sample [17]. The field homogeneity at present is about 25 ppm. It will be improved to the ppm level using mechanical shimming methods and a set of electrical shim coils. The field integral in the storage region is known at present to better than 1 ppm at any time and field drifts of a few ppm/hour were observed. It can be expected that with additional shimming and thermal insulation for the magnet yoke the field path integral can be known to 0.1 ppm.

The weak focussing is provided by electrostatic quadrupole field electrodes with 10 cm separation between opposite plates. They cover four 39° sections of the ring. The electric field is applied by pulsing a voltage of ±24.5 kV for ≈ms duration to avoid trapping of electrons and electrical breakdown [18].

Due to parity violation in the weak muon decay process the positrons are emitted preferentially in/opposite to the muon spin direction causing a time dependent variation of the spatial distribution of decay particles in the muon eigensystem which translates into a time dependent variation of the energy distribution observed by detectors fixed inside the ring.

The improvements over previous experiments include an azimuthally symmetric iron construction for the magnet with superconducting coils, a larger gap and higher homogeneity of the field, an electron/positron detector system covering a larger solid angle and using segmented detectors and improved electronics. A major advantage is the two orders of magnitude higher primary proton intensity available at the AGS Booster at BNL. A new feature will be ultimately the direct injection of muons into the storage volume using an electromagnetic kicker as compared to filling the ring with decay muons from injected pions which has been employed so far.

In order for the new muon g-2 experiment to reach its design accuracy besides the field also the muon mass respectively its magnetic moment needs to be known to 0.1 ppm or better. An improvement beyond the present 0.36 ppm

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g-2 magnet profile
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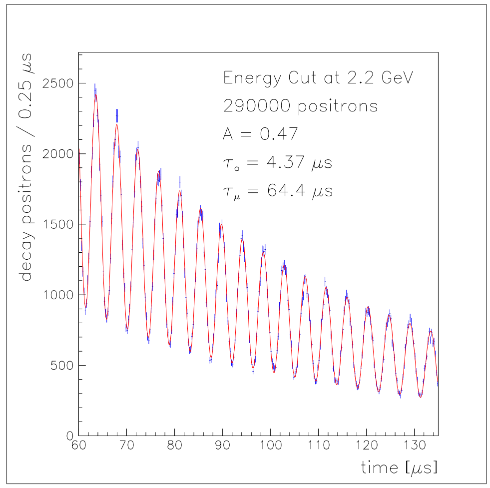

Figure 1. Cross sectional view of the magnet iron construction (left). Preliminary analysis of the observed muon spin precession signal in the new experiment (right).

accuracy of this constant can be expected from both microwave spectroscopy of the muonium atom's (μ^+e^-) hyperfine structure and from laser spectroscopy of the muonium 1s-2s transition [19].

3. Experiments beyond Muon g-2 using the Ring

The large installation with the highly homogeneous field seems to be attractive for further experiments. Of particular interest are applications where the homogeneous field is used in a mass spectrometer.

3.1. Particle Physics Experiments

Among the seriously discussed suggestions are the use of the magnet for searching for a finite mass of the muon neutrino [20]. By injecting relativistic pions and comparing the positions of the decay muons after one single turn in the magnet with the ones of pions one can expect a sensitivity to about 8 keV/c^2 which is 20 times better than the present limit [21]. Due to relativistic kinematics this method is less sensitive to the precision of the present knowledge of the pion mass compared to the previously employed technique [21].

A very promising approach seems to be the proposed search for a permanent electric dipole moment of the muon [22]. For such an experiment major modifications of the magnet setup would be required which involve the application of a radial electric field and the switching from electrostatic to alternating gradient focussing by replacing the pole tips of the magnet with appropriately shaped pieces of iron. In case of a finite electric dipole moment a time dependent asymmetry in the muon decay rates counted above and below the storage region is expected as a signature. Such an experiment may achieve up to four orders of magnitude improvement and could reach a level of sensitivity at which several theoretical models, particularly such involving supersymmetry, could be tested.

3.2. Heavy Ion Physics Possibilities

In the field of stored heavy ions unfortunately the weak focussing device cannot be expected to contribute to studies of and searches for crystalization of ion beams, as this phenomenon is prohibited by instabilities caused by radial deplacement dependent particle precession [23]. However, if the field homogeneity were sacrificed for alternating gradients and just the basic circular topology of the iron yoke and the field exciting coils were kept, one would have a chance to observe the effect.

The highly homogeneous field of the g-2 magnet looks promising for precision mass measurements of heavy ions. The field homogeneity and the accurate knowledge of the field integral can only be maintained, if the field is kept at a constant level. Therefore, only such experiments can be considered which do not need any variation of the field, i.e. the momentum of the particles to be injected into the ring needs to be adjusted appropriately. Among the possibilities one can expect accurate determinations of differences between very close masses, e.g. isomers, through their slightly different orbits and rotation frequencies. Neighbouring isotopes could be compared by additionally varying the momentum of different particles to be compared in their masses prior to injection.

4. Conclusions

The new Brookhaven g-2 magnet is a powerful device which is expected to guarantee the success of the experiment it has been designed for. Important questions in particle physics can be addressed with minor modifications subsequently.

Finally the concept of a circular uniform iron ring yoke with four circular coils for field excitation may find applications in precision heavy ion measurements.

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